Agricultural and Forest Meteorology 263 (2018) 90–99

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Interactive effects of seasonal drought and nitrogen deposition on carbon fluxes in a subtropical evergreen coniferous forest in the East Asian monsoon region

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ARTICLE INFO

Keywords:
CLM4.5
Carbon fluxes
Seasonal drought
Nitrogen deposition
Interactive effects

ABSTRACT

Subtropical forests in the East Asian monsoon region function as considerable carbon sinks in the Northern Hemisphere. Forest ecosystems in this region have experienced intensified seasonal drought that has limited their carbon sequestration capacity, but increasing atmospheric nitrogen deposition has contrarily enhanced their capacity to act as carbon sinks. Understanding and quantifying the interactive effects of seasonal drought and nitrogen deposition on the carbon sequestration of subtropical forests is of great significance for accurately predicting future changes to the terrestrial carbon cycle. In this study, we used the Community Land Model Version 4.5 (CLM4.5) to investigate how carbon fluxes, i.e. gross primary productivity (GPP), ecosystem respiration (Re), and net ecosystem productivity (NEP), respond to seasonal drought and nitrogen deposition in an evergreen coniferous forest in southern China. Our results showed that reduced GPP during the drought in the summers of 2003 and 2007 weakened the forest's carbon sequestration capacity. The reduction in GPP mainly occurred at the sunlit canopy due to its higher sensitivity to soil water stress, and non-stomatal limitations played an important role in limiting leaf photosynthesis. The enhanced NEP by nitrogen deposition was attributed to increased plant growth, which could, in turn, be attributed to increases in leaf area. Interactions of seasonal drought and nitrogen deposition varied with drought severity. Interactive effects of the two drivers on GPP, Re, and NEP were additive under mild and moderate drought conditions but non-additive under severe drought. Their net effects on NEP shifted from +29% under mild and moderate drought conditions to -56% under severe drought. Our study highlights the importance of accounting for the interactive effects of seasonal drought and nitrogen deposition in assessing the carbon sequestration of subtropical forest ecosystems in the East Asian monsoon region.

1. Introduction

Subtropical forests in the East Asian monsoon region function as considerable carbon (C) sinks in the Northern Hemisphere, accounting for 8% of the global forest net ecosystem productivity (NEP) (Yu et al., 2014). Under the control of subtropical high over the western Pacific, summer droughts accompanied by heatwaves occur frequently in this subtropical humid zone (Amulya et al., 2018; He et al., 2015), and significantly reduce carbon fluxes of forest ecosystems there and even the regional C budget (Liu et al., 2014; Saigusa et al., 2010; Sun et al., 2006; Xie et al., 2016). For example, a severe summer drought in southern China from July to August in 2013 caused a strong carbon uptake reduction of 101.54 Tg C, which was 39–53% of the annual net C sink of China's terrestrial ecosystems (Yuan et al., 2016). In this study

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https://doi.org/10.1016/j.agrformet.2018.08.009
Received 12 January 2018; Received in revised form 3 August 2018; Accepted 14 August 2018

we defined drought as a soil moisture deficit that restricts physiological processes such as photosynthesis and respiration (Baldocchi, 2008), because soil moisture deficit was found to be the main factor controlling carbon fluxes during seasonal drought in subtropical forests (Granier et al., 2007). Previous studies mainly focus on the investigation on how C and water fluxes respond to seasonal drought using eddy-covariance measurements (Liu et al., 2006; Song et al., 2006; Sun et al., 2006; Tang et al., 2014a,b; Wen et al., 2006, 2010; Yu et al., 2008b). They found that ecosystem gross primary productivity (GPP) is more sensitive to summer drought than ecosystem respiration (Re) in subtropical forests, which is consistent with studies in Europe and the globe (Ciais et al., 2005; Schwalm et al., 2010; Shi et al., 2014). However, the responses of physiological processes (e.g. enzymatic activities and stomatal conductance) to seasonal drought in the humid subtropical zone and their relative contributions to the reduction in carbon fluxes have not been well quantified yet.

Atmospheric nitrogen (N) deposition has increased significantly in the subtropical region of China (Liu et al., 2013), and is expected to further increase in the coming decades (Galloway et al., 2004; Kanakidou et al., 2016). It has a positive effect on subtropical forest productivity (Chen et al., 2015; Lebauer and Treseder, 2008), and is considered to be a large contributor to the increasing terrestrial NEP in this region (Fu et al., 2015; Wei et al., 2012; Yu et al., 2014) and the whole country of China (Gu et al., 2015; Tian et al., 2011). Results from meta-analysis and modeling suggested that the response of plant production to N addition varies with precipitation or water availability (Hooper and Johnson, 1999; Yahdjian et al., 2011). Since the terrestrial C cycle is closely coupled with N and water cycles, understanding the interactions between N and water availability seems to be more crucial for the prediction of terrestrial C cycle and its feedback to climate change under the circumstance with increasing N deposition and drought events.

Ecosystem responses to multiple global change drivers might be additive (i.e. the combined effect is equal or not significantly different from the sum of individual effects) or non-additive (i.e. synergistic or antagonistic, which means that the combined effect is significantly greater or weaker than the sum of individual effects). Across all two-driver pairs of global change drivers among elevated CO_2 (eCO_2), warming, N addition, phosphorus addition, increased rainfall, and drought, unlike the common additive interactions, there were synergistic effects of eCO_2 × warming and eCO_2 × N addition, and antagonistic effects of N addition × drought on plant C pools as revealed in a global meta-analysis (Yue et al., 2017). Nevertheless, scarce studies focus on the interactive effects of drought and N deposition on ecosystem carbon fluxes (Meyer-Grünefeldt et al., 2013; Niu et al., 2009), especially in forest ecosystems subjected to drought (Drewniak and Gonzalez-Meler, 2017).

In this study, we applied the Community Land Model Version 4.5 (hereafter referred to as CLM4.5), which couples C, N, and water cycle explicitly, to analyze the changes in ecosystem carbon fluxes and related plant physiological processes under the summer drought conditions of 2003 and 2007 in a subtropical evergreen coniferous forest in southern China. The scientific questions addressed in this study included: (1) How do plant physiological processes respond to drought, and how do these contribute to decreased carbon fluxes during seasonal drought periods? (2) How do carbon fluxes respond to seasonal drought and N addition individually? (3) Are there interactive effects of seasonal drought and N addition on ecosystem carbon fluxes and whether they are additive or not? We hypothesized that the combined effects of N deposition and seasonal drought on terrestrial carbon fluxes in subtropical forests will be significantly different from the sum of individual effects (i.e. non-additive effects).

Table 1
The differences in air temperature (T), precipitation (P), soil water content (SWC) in July of drought years (2003 and 2007) and baseline years (2004–2006 and 2008).

Environmental variable	Differences between drought and baseline years		Baseline years (mean ± 1SE)
	2003	2007	
T (°C)	3.07*	1.58	28.83 ± 1.81
P (mm mon^{-1})	−88.81*	−90.01*	92.7 ± 27.59
SWC ($m^3 m^{-3}$)	−0.048*	−0.043*	0.369 ± 0.025

*represents significant differences ($P < 0.05$) in July between drought and baseline years.

2. Materials and methods

2.1. Site description

The Qianyanzhou (QYZ) subtropical coniferous forest site is part of the ChinaFlux network and is located in southeast China (26°44′29″N, 115°03′29″E, elevation 102 m). The forest site has a subtropical monsoon climate with warm and dry winters, and hot and wet summers. The mean annual air temperature and annual precipitation are 18 °C and 1505 mm, respectively, according to the meteorological records of 1989–2008. Precipitation during July-August has a high inter-annual variability influenced by the subtropical high over the western Pacific. Total precipitation in July of 2003 and 2007 was significantly lower than that in baseline years. At the same time, the mean monthly air temperature in July was also higher than baseline value. Consequently, the summer drought occurred when the soil water contents were significantly lower than baseline value (Table 1). The original vegetation of this site was evergreen broadleaf forest, which was harvested around 1950 (Huang et al., 2007). The current evergreen coniferous plantation was planted around 1985 on gently undulating terrain with slopes between 2.8 and 13.5 degrees. The dominant tree species now are Slash pine (*Pinus elliottii*), Masson pine (*Pinus massoniana*), and Chinese fir (*Cunninghamia lanceolata*), with a tree density of approximately 1460 stems ha^{-1} and a mean canopy height of 13 m (Wen et al., 2006). The soil is weathered from red sand rock, and the soil texture is categorized as 2.0–0.05 mm (17%), 0.05–0.002 mm (68%) and < 0.002 mm (15%) (Yang, 2005).

2.2. Eddy-covariance and meteorological data

Eddy covariance instruments, which consist of open-path analyzer, infrared gas analyzers for CO_2 and water vapor, three-dimensional sonic anemometer, and a data acquisition system, were mounted at 39.6 m on a tower. The tower footprint has a length of 1915 m (Mi et al., 2006). A half-hourly NEP was estimated over the canopy by calculating CO2 storage below the height of the flux measurement system. The data gaps of NEP were filled mainly by the nonlinear regressions method (Falge et al., 2001). Observed GPP and Re were estimated from half-hourly NEP following Zhang et al. (2006). Estimated NEP data provided by ChinaFLUX for this forest ecosystem was quite well consistent with those estimated by JapanFlux and KoFlux (Saigusa et al., 2013). These flux observations have been successfully used in the earlier studies on effects of seasonal drought on carbon and water fluxes, water use efficiency, and the Bowen ratio (Song et al., 2006; Sun et al., 2006; Tang et al., 2014a; Wen et al., 2010; Yu et al., 2008a). In this study, observed NEP, GPP, and Re were aggregated at a daily step to evaluate the performance of CLM4.5. Further details about the instruments and data quality evaluation technique are provided in Wen et al. (2010).

Meteorological variables and soil water content were also measured at the site (Wen et al., 2010). Half-hourly climate data (i.e. air